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Video hologram and device for reconstructing video holograms

The present invention relates to a video hologram and a device for reconstructing video holograms comprising an optical system, that consists of at least one light source, a lens and a hologram-bearing medium composed of cells arranged in a matrix or an otherwise regular pattern with at least one opening per cell, the phase or amplitude of said opening being controllable, and a viewing plane located in the image plane of the light source.

Devices for reconstructing video holograms using acousto-optical modulators (AOM) are known from prior art (Stephen A. Benton, Joel S. Kollin: Three dimensional display system, US 5,172,251). Such acousto-optical modulators transform electric signals into optical wave fronts, which are recomposed in a video frame using deflection mirrors to form two-dimensional holographic areas. A scene visible for the viewer is reconstructed from the individual wave fronts using further optical elements. The optical means used, such as lenses and deflection elements, have the dimensions of the reconstructed scenes. Due to their great depth, these elements are voluminous and heavy. It is difficult to miniaturise them, so that their range of applications is limited.

Another possibility to generate large video holograms is provided by the so-called "tiling method", using computer-generated holograms (CGH). In this method, known from WO 00/75698 A1 and US 6,437,919 B1, small CGHs having a small pitch are composed with the help of an optical system. For this, in a first step, the required information is written to fast matrices having a small pitch (usually EASLM [electronically addressable spatial light modulators]), and then the matrices are reproduced on to a suitable holographic medium and composed to form a large video hologram. Usually, an optically addressable spatial light modulator (OASLM) is used as holographic medium. In a second step, the composed video hologram is reconstructed with coherent light in transmission or reflection.

In the CGH with controllable openings arranged in a matrix or in an otherwise regular pattern, known e.g. from WO 01/95016 A1 or *Fukaya et al., "Eye-position tracking type electro-holographic display using liquid crystal devices", Proceedings of EOS Topical Meeting on Diffractive Optics, 1997*, the diffraction on small openings is taken advantage of for encoding the scenes. The wave fronts emerging from the openings converge in object points of the three-dimensional scene before they reach the viewer. The smaller the pitch, and thus the smaller the openings in the CGHs, the greater is the diffraction angle, i.e. the viewing angle. Consequently, with these known methods enlarging the viewing angle means to improve the resolution.

As is generally known, in Fourier holograms the scene is reconstructed as a direct or inverse Fourier transform of the hologram in a plane. This reconstruction is continued periodically at a periodicity interval, the extension of said periodicity interval being inversely proportional to the pitch in the hologram.

If the dimension of the reconstruction of the Fourier hologram exceeds the periodicity interval, adjacent diffraction orders will overlap. As the resolution is gradually decreased, i.e. as the pitch of the openings rises, the edges of the reconstruction will be distorted increasingly by overlapping higher diffraction orders. The usable extent of the reconstruction is thus gradually limited.

If greater periodicity intervals and thus greater viewing angles are to be achieved, the required pitch in the hologram comes closer to the wavelength of the light. Then, the CGHs must be sufficiently large in order to be able to reconstruct large scenes. These two conditions require a large CGH having a great number of openings. However, this is currently not feasible in the form of displays with controllable openings (see EP 0992163 B1). CGH with controllable openings only measure one to several inches, with the pitches still being substantially greater than 1 μm.

The two parameters, pitch and hologram size, are characterised by the so-called space-bandwidth product (SBP) as the number of openings in the hologram. If the reconstruction of a CGH with controllable openings that has a width of 50 cm is to be generated so that a viewer can see the scene at a distance of 1 m and in a 50-cm-wide horizontal viewing window, the SBP in horizontal direction is about $0.5 \cdot 10^6$. This corresponds to 500,000 openings at a distance of 1 μm in the CGH. Assuming an aspect ratio of 4:3, 375,000 openings are required in the vertical direction. Consequently, the CGH comprises $3.75 \cdot 10^{11}$ openings, if three colour sub-pixels are taken into consideration. This number will triplicate if the fact is taken into account that the CGH with controllable openings usually only allows the amplitudes to be affected. The phases are encoded taking advantage of the so-called detour phase effect, which requires at least three equidistant openings per sampling point. SLM having such a great number of controllable openings are hitherto unknown.

The hologram values must be calculated from the scenes to be reconstructed. Assuming a colour depth of 1 Byte for each of the three primary colours and a frame rate of 50 Hz, a CGH requires an information flow rate of $50 * 10^{12} = 0.5 * 10^{14}$ Byte/s. Fourier transformations of data flows of this magnitude exceed the capabilities of today's computers by far and do thus not allow holograms to be calculated based on local computers. However, transmitting such an amount of data through data networks is presently unfeasible for normal users.

In order to reduce the enormous number of computations it has been proposed not to calculate the entire hologram, but only such parts of it that can be seen directly by the viewer, or such parts that change. The kind of hologram which consists of addressable sub-regions, such as the above-mentioned "tiling hologram", is disclosed in the above-mentioned patent specification WO 01/95016 A1. Starting point of the calculations is a so-called effective exit pupil, the position of which can coincide with the eye pupil of the viewer. The image is tracked as the viewer position changes by continuous recalculation of the hologram part that generates the image for the new viewer position. However, this partly nullifies the reduction in the number of computations.

The disadvantages of the known methods can be summarised as follows: Arrangements with acousto-optical modulators are too voluminous and cannot be reduced to dimensions known from state-of-the-art flat displays; video holograms generated using the tiling method are two-stage processes which require enormous technical efforts and which cannot easily be reduced to desktop dimensions; and arrangements based on SLM with controllable openings are too small to be able to reconstruct large scenes. There are currently no large controllable SLM with extremely small pitches, which would be needed for this, and this technology is further limited by the computer performance and data network bandwidth available today.

It is an objective of the present invention to circumvent the above-mentioned disadvantages and to provide extended real-time reconstructions of video holograms at large viewing angles.

According to the present invention, this objective is solved in an inventive manner by a video hologram and a device for reconstructing video holograms having the features of claim 1. Preferred embodiments of the invention are laid down in claims 2 to 10.

The video holograms and devices for reconstructing video holograms with controllable openings according to the present invention are characterised in that in the viewing plane at least one viewing window is formed in a periodicity interval as a direct or inverse Fourier transform of the video hologram, said viewing window allowing a viewer to view a reconstruction of a three-dimensional scene. The maximal extent of the viewing window corresponds to the periodicity interval in the plane of the inverse Fourier transformation in the image plane of the light source. A frustum stretches between the hologram and the viewing window, said frustum containing the entire three-dimensional scene as Fresnel transform of the video hologram.

The viewing window in the present invention is limited approximately to and positioned in relation to one eye, an eye distance of a viewer or to another suitable area.

Now, in this invention, another viewing window is provided for the other eye of the viewer. This is achieved by the fact that the observed light source is displaced or added a second, real or virtual, adequately coherent light source at another suitable position to form a pair of light sources in the optical system. This arrangement allows the three-dimensional scene to be seen with both eyes through two associated viewing windows. The content of the video hologram can be changed, i.e. re-encoded, according to the eye position in synchronism with the activation of the second viewing window. If several viewers view the scene, more viewing windows can be generated by turning on additional light sources.

As regards another aspect of the present invention of the device for reconstructing a video hologram, the optical system and the hologram-bearing medium are arranged so that the higher diffraction orders of the video hologram have a zero point for the first viewing window or an intensity minimum at the position of the second viewing window. This prevents the viewing window for one eye to cross-talk the other eye of the viewer or to other viewers. It is thus taken advantage of the decrease in intensity of the light towards higher diffraction orders, which is due to the finite width of the openings of the hologram-bearing medium and/or the minima of the intensity distribution. The intensity distribution for rectangular openings, for example, is a sinc^2 function which rapidly decreases in amplitude and forms a $\sin^2$ function which decreases as the distance grows.

The number of openings in the display determines the maximum number of values that must be calculated for the video hologram. The transmission of data from a computer or through a network to the display representing the video hologram is limited to the same number of values. The data flow rate does not substantially differ from the data flow rates known from typical displays used today. Now, this will be illustrated with the help of an example.

If the viewing window is reduced, for example, from 50 cm (horizontal) by 37.5 cm (vertical) to 1 cm by 1 cm by choosing a sufficiently low-resolution display, the number of openings in the hologram will drop to 1/1875. The required bandwidth is reduced in the same way during data transmission through a network. Video holograms created with known methods require 10^{12} openings, while this number is reduced to $5 \cdot 10^8$ pixels in this example. The scene can be viewed in full through the remaining viewing window. These requirements on pitch and hologram size according to the space-bandwidth product can already be fulfilled by displays available today. This allows to inexpensively realise large real-time video holograms on displays with large pitch for a large viewing window.

The viewing window is tracked by mechanically or electronically displacing the light sources, by using movable mirrors or by using light sources which can be adequately positioned in any other way. The viewing windows are displaced according to the displacement of the light source images. If the viewer moves, the light source(s) is (are) spatially displaced so that the viewing windows follow the eyes of the viewer(s). This is to ensure that the viewers can also see the reconstructed three-dimensional scene when they move, so that their freedom of movement is not limited. Several systems are known for detecting the position of the viewers, e.g. systems based on magnetic sensors can be used beneficially for this.

This invention also allows to reconstruct a video hologram efficiently in colour. Here, the reconstruction is performed with at least three openings per cell, representing the three primary colours, amplitude or phase of said openings being controllable, and said openings being encoded individually for each of the primary colours. Another possibility of reconstructing a video hologram in colour is to perform at least three reconstructions one after another, namely for the individual primary colours, using the device of the present invention.

The present invention allows to efficiently generate holographic reconstructions of spatially extended scenes through controllable displays, such as TFT flat screens, in real-time and providing large viewing angles. These video holograms can be used beneficially in TV, multimedia, game and design applications, in the medical and military sectors, and in many other areas of economy and society. The three-dimensional scenes can be generated by a computer or in any other way.

An embodiment of the present invention is illustrated and explained below in conjunction with the accompanying drawings, wherein

Fig. 1 is a general illustration of a video hologram and a device for reconstructing video holograms showing the generation of the diffraction orders and the position of a viewing window;

Fig. 2 is a general illustration of a device for reconstructing video holograms showing a three-dimensional scene which can be viewed through a viewing window;

Fig. 3 is a general illustration of a device for reconstructing video holograms showing the encoding of the three-dimensional scene in a part of the video hologram;

Fig. 4 is a diagram showing the light intensity distribution in the viewing plane depending on the diffraction orders; and

Fig. 5 is a general illustration of a device for reconstructing video holograms showing the position of the viewing windows for both eyes of a viewer with regard to the diffraction orders to prevent cross-talking.

A device for reconstructing video holograms comprises the hologram-bearing medium, a sufficiently coherent, real or virtual, point or line light source and an optical system. The video hologram-bearing medium itself consists of cells which are arranged in a matrix or in an otherwise regular pattern with at least one opening per cell, the phase or amplitude of said opening being controllable. The optical system for reconstructing the video hologram can be realised by an optical imaging system known in the art, consisting of a point or line laser or a sufficiently coherent light source.

Fig. 1 shows the general arrangement of a video hologram and its reconstruction. A light source 1, a lens 2, a hologram-bearing medium 3 and a viewing plane 4 are arranged one after another, seen in the direction of the propagating light. The viewing plane 4 corresponds with the Fourier plane of the inverse transform of the video hologram with the diffraction orders.

The light source 1 is imaged on to the viewing plane 4 through an optical system, represented by the lens 2. If a hologram-bearing medium 3 is inserted, it is reconstructed in the viewing plane 4 as an inverse Fourier transform. The hologram-bearing medium 3 with periodic openings creates equidistantly staggered diffraction orders in the viewing plane 4, where the holographic encoding into higher diffraction orders takes place, e.g. by way of the so-called detour phase effect. Because the light intensity decreases towards higher diffraction orders, the 1st or –1st diffraction order is used as the viewing window 5. If not explicitly expressed otherwise, the 1st diffraction order will be taken as a basis in the further description of the invention.

The dimension of the reconstruction was chosen here to correspond with the dimension of the periodicity interval of the 1st diffraction order in the viewing plane 4. Consequently, higher diffraction orders are attached without forming a gap, but also without overlapping.

Being the Fourier transform, the selected 1st diffraction order forms the reconstruction of the hologram-bearing medium 3. However, it does not represent the actual three-dimensional scene 6. It is only used as the viewing window 5 through which the three-dimensional scene 6 can be observed (see Fig. 2). The actual three-dimensional scene 6 is indicated in the form of a circle inside the bundle of rays of the 1st diffraction order. The scene is thus located inside the reconstruction frustum which stretches between the hologram-bearing medium 3 and the viewing window 5. The scene 6 is rendered as the Fresnel transform of the hologram-bearing medium 3, whereas the viewing window 5 is a part of the Fourier transform.

Fig. 3 shows the corresponding holographic encoding. The three-dimensional scene is composed of discrete points. A pyramid with the viewing window 5 being the base

and the selected point 7 in the scene 6 being the peak, is prolonged through this point and projected on to the hologram-bearing medium 3. A projection area 8 is created in the hologram-bearing medium 3 that point being holographically encoded in said projection area. The distances between the point 7 to the cells of the hologram-bearing medium 3 can be determined in order to calculate the phase values. This reconstruction allows the size of the viewing window 5 to be constrained by the periodicity interval. If, however, the point 7 was encoded in the entire hologram-bearing medium 3, the reconstruction would extend beyond the periodicity interval. The viewing zones from adjacent diffraction orders would overlap, which would result in the viewer seeing a periodic continuation of the point 7. The contours of a thus encoded surface would appear blurred due to multiple overlapping.

The intensity decrease towards higher diffraction orders is taken advantage of to suppress cross-talking to other viewing windows. Fig. 4 shows schematically a light intensity distribution over the diffraction orders, said distribution being determined by the width of the openings in the CGH. The abscissa shows the diffraction orders. The 1st diffraction order represents the viewing window 5 for the left eye, i.e. the left viewing window, through which the three-dimensional scene can be viewed. Cross-talking into a viewing window for the right eye is suppressed by the decrease in light intensity towards higher diffraction orders and, additionally, by the zero point of the intensity distribution.

Of course, the viewer can view the scene 6 of the hologram 3 with both eyes (see Fig. 5). For the right eye, the right viewing window 5' represented by the –1st diffraction order of the light source 1' was chosen. As can be seen in the drawing, this light influences the left eye at a very low intensity. Here, it corresponds to the –6th diffraction order.

For the left eye, the 1st diffraction order corresponding to the position of the light source 1 was chosen. The left viewing window 5 is formed likewise. According to this invention, the corresponding three-dimensional scenes 6 and 6' (not shown) are reconstructed using the light sources 1 and 1' in a fix position in relation to the eyes. For this, the hologram 3 will be re-encoded when the light sources 1 and 1' are turned on. Alternatively, the two light sources, 1 and 1', can simultaneously reconstruct the hologram 3 in the two viewing windows 5 and 5'.

If the viewer moves, the light sources 1 and 1' are tracked so that the two viewing windows 5 and 5' remain localised on the eyes of the viewer. The same applies for movements in the normal direction, i.e. perpendicular to the video hologram.

Further, several viewers can view a three-dimensional scene if additional viewing windows are created by turning on additional light sources.